Hybrids

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Abstract

The well–known selection rule for the strong decays of hybrid mesons is noted to be more general than specific models. We report a detailed calculation in two flux–tube models of the photoproduction of hybrid mesons via meson exchange. The importance of translating estimates for the $\rho\pi$ couplings of states produced at BNL and VES to photoproduction couplings is emphasized. We indicate that diffractive photoproduction of hybrids can possibly be significant at TJNAF.

1 Introduction

Hybrids are bound states where there is an explicit excitation of the gluon field of QCD. The valence structure is quark–antiquark–glue. Why are hybrids important?

- They represent confined states predicted by lattice QCD [1, 2, 3] and their existence constitutes an important experimental test for QCD.
- Hybrids provide a window on the non–perturbative gluon fields of QCD.

Hybrids often have exotic quantum numbers not found for conventional mesons in the quark model, e.g. $J^{PC} = 0^{--},\ 0^{+-},\ 1^{-+},\ 2^{+-},\ 3^{-+},\ldots$. Exotic J^{PC} immediately identifies the state as not being a conventional meson.

2 J^{PC}, masses and decays of hybrids

In the limit of adiabatically moving quarks lattice gauge theory predicts the quantum numbers of the lowest–lying hybrids to be $J^{PC} = 1^{--}, 1^{++}, (0,1,2)^{-+}$, $(0,1,2)^{+-}$ [4, 5]. For adiabatically moving quarks the gluonic degrees of freedom are assumed to adjust themselves instantaneously as the quarks move.

There are two lattice gauge theory groups that have predicted $s\bar{s}$ 1^{-+} masses, the UKQCD [1] and MILC collaborations [2, 3]. These groups have considerable facility to seperate the lightest 1^{-+} state for a given mass quarks. MILC has presented evidence that operators, whether they are hybrid–like or four–quark like, easily select the lowest–lying state, indicating a strong coupling of either operator to the 1^{-+} state. It is important to emphasize that quenched lattice calculations allow Fock state components with $Q\bar{Q}$ and $Q\bar{Q}Q\bar{Q}$ quark structure, and that the quark Fock state decomposition of the lowest–lying 1^{-+} is by no means determined by these calculations. Although lattice calculations in the quenched approximation contain contamination from higher excited states and lattice artifacts, they are settling down on an $s\bar{s}$ mass estimate. UKQCD estimates 1990 ± 130 MeV, where the error is statistical. MILC quotes 2170 ± 80 MeV with an additional ~ 200 MeV systematic error. Systematic errors do not include errors due to the quenched approximation. Taking the mass difference between light and $s\bar{s}$ hybrids to be similar to conventional mesons, we expect light quark hybrids to be $\sim 200 - 250$ MeV lighter [6], i.e. $(1.75 - 2) \pm 0.2$ GeV. In fact, MILC finds 1970 ± 90 MeV from an extrapolation of hybrid masses to light quarks, with a systematic error of 300 MeV [2, 3].

Flux–tube models predict that light hybrids are in the $1.8 - 1.9$ GeV range [7], in accord with estimates from lattice gauge theory.

As far as decays go, significant recent progress has been made in understanding the well–known selection rule that broadly states that "hybrid decays to S–wave mesons are suppressed". A precise formulation of the selection rule has been proved to be that [8]

The connected decay and production of adiabatic hybrids coupling to S–wave conventional mesons which are identical in all respects, except possibly flavour and spin, vanish for non–relativistic quarks with spin 1 pair creation. The quark content of the hybrid is either flavour $Q\bar{Q}$ or $Q\bar{q}$ ($Q \neq q$), where the latter is only relevant to decay topologies involving only u, d quarks where isospin symmetry is assumed.

The central assumptions needed for the validity of the selection rule has been shown to be that the quarks must move adiabatically, non–relativistically and that they must decay in a simple connected decay topology via spin 1 pair creation [8].

It has been shown in ref. [8] that all model calculations in constituent gluon models and flux–tube models obey the selection rule when the necessary conditions are met by these models.

The selection rule requires the final state mesons to be identical in all respects, except possibly in their flavour and spin wave functions. Thus if the final state mesons have different spatial wave functions, we expect breaking of the selection rule. This "lifting of suppression" can be rigorously defined in flux–tube models (see Eq. 2 below) and for $\omega\pi$, $\rho\pi$, $\omega\eta$ and $\rho\eta$ was estimated to be 20% [9]. For final states with (almost) identical wave functions like $\rho\rho$, $\omega\omega$ and $\rho\omega$ the selection rule remains unbroken.

In photoproduction, where the photon is viewed as an off–shell ρ, ω or ϕ via vector meson dominance (VDM), which interacts with an off–shell exchanged meson to produce a hybrid, it is clear that the wave function of the incoming ρ, ω or ϕ is very different from that of the exchanged particle, so that substantial lifting of suppression is expected. We hence conclude that meson exchange can be a significant production mechanism for hybrids [9]. Photoproduction of hybrid mesons at an upgraded Continuous Electron Beam Accelerator Facility (CEBAF) at TJNAF could hence be significant, due to the predominance of π exchange at CEBAF's energy [10].

We shall assume throughout this work that s–channel and u–channel production of states in the mass range of interest are suppressed, since very heavy ≈ 3 GeV excited nucleons would have to be produced for this mechanism to be viable.

3 Photoproduction of hybrid mesons by meson exchange in flux–tube models

Experimentally, little has been published about the photoproduction of hybrids. Condo *et al.* reported an isovector state in $\rho\pi$ with mass 1775 MeV with a width of $100-200$ MeV with J^{PC} either 1^{-+}, 2^{-+} or 3^{++} in a 19.3 GeV photon beam [11]. Since there is the possibility that this state has exotic J^{PC}, it could be a photoproduced hybrid. Photoproduction and electroproduction experiments have been proposed which will study hybrid production at the CLAS spectrometer at TJNAF [12, 13].

On the theoretical side, only ref. [10] has attempted to address the photoproduction of hybrids. This was done in a flux–tube model. The approach was to seperate out the width Γ as

$$\Gamma = \mathcal{R}\,\Gamma_R \tag{1}$$

with Γ_R the "reduced width" and

$$\mathcal{R} = (\frac{\beta_B^2 - \beta_C^2}{\beta_B^2 + \beta_C^2})^2 \qquad (2)$$

the "lifting of suppression". The reduced width gives an indication of the intrinsic size of coupling, since $\mathcal{R}$ is extremely dependent on the detailed values assumed for the inverse S.H.O. wave function radii $\beta_{B,C}$ of the final state mesons B and C. It is not possible to obtain accurate estimates for $\beta_{B,C}$ at this time, partially due to the fact that the sizes of off–shell mesons participating in photoproduction processes (see above) is not well understood.

The approach of ref. [10] is to use Γ_R as an upper limit on the strength of production of the hybrid, and then to correct for the coupling of the ρ, ω or ϕ to the photon by the appropriate VDM factor.

Until now we neglected the possible diffractive production of hybrid mesons by photons. Diffractive exchange $\mathcal{P}$ is believed to be neutral and to have charge conjugation $C = +$. It follows that in photoproduction, charged isovector hybrids cannot be produced via diffractive exchange, due to the fact that $\mathcal{P}$ is neutral. Similarly, $C = +$ neutral hybrids cannot be produced via diffractive exchange, due to C–parity conservation and the fact that $\mathcal{P}$ has $C = +$.

This has the significant consequence that a large subset of hybrids produced in photoproduction can only be produced in meson exchange. This is true of charged isovector 1^{--}, $(0,1,2)^{+-}$ hybrids and 1^{++}, $(0,1,2)^{-+}$ hybrids. One of the important conclusions is that exotic 1^{-+} hybrid production can only be via meson exchange.

We have carried out a numerical simulation in the Isgur–Paton–Kokoski flux–tube model [14] and the Page–Swanson–Szszepaniak flux–tube model [15]. The production of hybrids made from light quarks were considered. The photon couples to ρ and ω and the exchanged meson is allowed to be π, η, ρ or ω. The detailed numerical simulations will be published elsewhere [16]. The salient features are that in the overall majority of cases, only the ρ coupling to the photon is needed to produce significant (> 50 keV) upper limits to the coupling. ω coupling to the photon consistently yields smaller total upper limits on the coupling than ρ coupling to the photon, if both type of couplings are allowed. Another feature of these simulations is that the two type of flux–tube models give very similar couplings, so that the couplings are approximately model–independent. Isoscalar 0^{-+} and exotic 2^{+-} are found to couple less than 50 keV for all considered meson exchange possibilities and isoscalar exotic 0^{+-} does not couple at all to any of the considered meson exchange possibilities.

4 The "$\rho\pi$ game"

Within the assumption of VDM, once you know the $\rho\pi$ coupling of a state, you can estimate the coupling in photoproduction via π exchange. Specifically of interest here is isovector mesons and hybrids which decay to $\rho\pi$. By G–parity conservation it follows that the state must have $C = +$, and hence that the state would not be produced diffractively in photoproduction. So we can turn the $\rho\pi$ coupling of a state that can be measured at pion beam experiments like VES and BNL around to estimate the π exchange contribution to photoproduction of the state, without having to invoke diffractive exchange.

$\rho\pi$ couplings can effectively be sampled at pion beam experiments, especially if it is known that the production mechanism involves natural parity exchange, i.e. most likely ρ exchange. If the state also decays to $\rho\pi$ this provides an easy way to estimate the coupling as will now be enunciated in some detail.

Estimates for $\rho\pi$ couplings can be obtained by noticing that the E852 pion beam experiment established that a_2, a_1 and $\pi_2(1670)$ are produced via natural parity exchange. The fact that the states also decay to $\rho\pi$, enables us to make a rough phenomenological estimate of the partial width of the states to $\rho\pi$. The number of events observed should be proportional to the coupling of the incoming pion to the exchanged ρ and the probability of decay of the state X to $\rho\pi$, i.e. to $\Gamma(X \to \rho\pi)\ BR(X \to \rho\pi)$. Hence,

$$\Gamma(X \to \rho\pi) \approx \sqrt{(\text{Number of events})_X (\text{Total width})_X} \tag{3}$$

We estimate[1] $R(X) \equiv \Gamma(X \to \rho\pi)/\Gamma(a_2 \to \rho\pi)$ according to Eq. 3 from E852 data in $\rho\pi$

$$R(a_1) \approx 2.9 \qquad R(\pi_2(1670)) \approx 1.2 \tag{4}$$

while estimates from the PDG gives

$$R(a_1) = 3.4 \qquad R(\pi_2(1670)) = 1.1 \tag{5}$$

It is clear that the naïve estimates of $R(X)$ from E852 data are in accord with expectations from the PDG, motivating the use of Eq. 3. We have thus demonstrated that $\rho\pi$ couplings can be extracted reliably. We urge experimenters perform a more comprehensive analysis.

[1] We estimate 100000, 370000, 60000 and 8000 events in unnatural parity exchange under the a_2, a_1 and $\pi(1670)$ Breit–Wigner peaks. The total widths used are respectively 107, 250 and 258 and the $\rho\pi$ widths used are respectively 74, 250 and 80 MeV [6].

5 Diffractive photoproduction

VES noted that "the wave $J^P = 0^-$ [$\pi(1800)$] dominates at low t, indicating diffractive exchange" [17]. Detailed studies of the decay modes of $\pi(1800)$ have established independently that it appears to fit the data as a hybrid candidate and not as a conventional meson [18, 19].

If VES's conclusions are reliable, we speculate that the hybrid can be produced significantly in diffraction. This is supported by naïve estimates which suggest that hybrid meson diffractive production should be enhanced above that of glueballs, conventional mesons and four–quark states, due to the presence $Q\bar{Q}$ *and* glue at the production vertex.

If hybrids are produced significantly in diffractive exchange, we expect the diffractive photoproduction of $J^{PC} = 1^{--}$ hybrids to be important. In fact, the states $\rho(1450)$, $\rho(1700)$, $\omega(1420)$ and $\omega(1600)$ have been observed in diffractive photoproduction. It is of significant interest that an independent study of the decay modes of some of these states finds evidence that $\rho(1450)$, $\rho(1700)$ and $\omega(1420)$ can be regarded as mixtures of hybrids and conventional mesons [9, 18]. This may indicate that hybrids have already been observed in diffractive photoproduction. The conclusions of ref. [18] depended critically on the influential data analysis of ref. [20] which finds that $\Gamma(\rho(1450) \to a_1\pi) \approx 190$ MeV, $\Gamma(\omega(1420) \to b_1\pi) \approx 0$ MeV and $\Gamma(\omega(1600) \to b_1\pi) \approx 30$ MeV. One of the goals of photoproduction of TJNAF should be to verify the accuracy of these partial widths.

We also point out that the neutral J^{PC} exotics 0^{+-} and 2^{+-} and the neutral non–exotic 1^{+-} can be produced in diffractive photoproduction. This is in analogy to experimental indications for the diffractive process $\pi N \to a_1 N$. However, diffractive production of 0^{+-} may be suppressed by S–channel helicity conservation since the incoming photon is transversely polarized.

6 Conclusions

- Decay selection rules for hybrids have been found to be more general than specific models, and the assumptions under which they can be derived have been exposed.
- Hybrids can be significantly produced in meson exchange.
- Pion beam experiments at VES and BNL can predict the strength of photoproduction via π exchange for states that couple to $\rho\pi$.

- Diffractive exchange may significantly produce hybrids.

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